Development of a Control Method for LLC Converter Utilized for Input-Parallel-Output-Series Inverter System with Solid-State Transformers

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A multi-level power converter with series-connected solid-state transformer (SST) units for a power conditioning system for photovoltaic (PV) generation was developed. Each SST unit has an LLC converter driven by SiC-MOSFETs and a high-frequency transformer. By applying the developed converter, the system can be optimized and made lighter than a conventional system using a commercial transformer. A method for controlling the LLC converter so as to maintain its high efficiency over a wide voltage range of a PV panel is proposed. According to the results of an experimental evaluation of a prototype SST unit, the efficiency of the LLC converter is 98% or more even when the input voltage from the PV panel changes.

Keywords: solid-state transformer, multi-level, LLC converter, SiC, efficiency, PCS

1. Introduction

As the practical use of wide-band-gap switching devices, such as ones based on SiC and GaN, the efficiency and switching frequency of power-conversion systems utilizing these devices have become higher. A solid-state transformer (SST) is one of the suitable power-conversion systems to which these devices are applied. Usually, an SST includes an isolated DC/DC converter with a high-frequency transformer driven at more than several kilohertz. This frequency range is significantly higher than that at which a commercial transformer is driven, namely, 50 or 60 Hz. Since the volume of a transformer reduces as the driving frequency becomes higher, the size and weight of the transformer can be reduced, thereby reducing the size and weight of the power-conversion system. Furthermore, as for an SST, the boost ratio between input and output voltages can be changed by controlling the DC/DC converter. Accordingly, an SST is expected to be applied to next-generation power systems such as smart grids. Also, as mentioned above, SiC devices are suitable for application as SSTs. The frequency of SiC devices can be made higher than that of conventional ones such as Si devices. Applying SiC devices to SSTs is thus effective for not only improving efficiency but also reducing size and weight of the system.

Recently, a modular-multi-level converter (MMC) for application to a high-voltage and large-power-supply system has been actively researched. An MMC consists of series-connected half-bridge or full-bridge units for each phase. It outputs a multi-level voltage by controlling the output of each unit. As a result, a sinusoidal output voltage with few harmonics can be generated. One of the features of an MMC is that it makes it possible to apply switching devices with lower rated voltage than a conventional power converter (such as two- or three-level converters) because the series-connected unit shares the output or input voltage. Since switching devices with lower rated voltage are more commonly used for various applications, the cost of such devices is lower than those with higher rated voltage. For this reason, MMCs have the potential to reduce the cost of a power-conversion system compared to a conventional system using switching devices with higher rated voltage.

Given the above-described situation, we have researched a multi-level power converter consisting of SST units whose inputs are connected in parallel and outputs are connected in series. A high-frequency (HF) transformer is implemented in each SST unit, and the input and output are insulated by the HF transformer. It is therefore possible to attain both a compact and lightweight system and insulation between the input and output. We previously applied a multi-level converter with multiple SST units to a power-conditioning system (PCS) for PV generation (PV-PCS). Each SST unit has an LLC converter as the isolated DC/DC converter. The LLC converter has both the high efficiency and low noise characteristics. Therefore, the size of each SST unit can be made small. However, as one of the features of the LLC converter, the controllable voltage range with high efficiency is narrow. In the case of PV-PCS, the input voltage fluctuates depending on the weather and time. Therefore, the wide controllable voltage range is needed to each SST unit.
In this paper, first of all, a concept of the multi-level converter assuming PV-PCS is described. Then, the control method which can satisfy with the wide controllable voltage range with high efficiency of an LLC converter is described.

2. Multi-level Converter with SST Units for PV-PCS

The system configuration of the developed multi-level converter for PV-PCS, as well as the circuit configuration and structure of the SST unit for PV-PCS, are described below.

2.1 Circuit Configuration of Developed Multi-level Converter for PV-PCS

In a PV-PCS, a converter receives DC power generated by PV panels. The PCS controls the DC voltage of the PV panels in order to maximize the generated power from the PV panels using a method called “maximum power point tracking (MPPT)”. Fig. 1(a) shows a conventional PV system. Each PV panel has a PCS, and its output is a three-phase AC voltage of several-hundred volts. Then, in the case of a PCS with a conventional converter, the three-phase AC voltage is boosted up to several kilovolts with a commercial sub-transformer connected to a commercial main transformer. These transformers are driven at 50 or 60 Hz. Therefore, in the power-conversion system, the size of these transformers are dominant. On the other hand, in the case of the developed multi-level converter shown in Fig. 1(b), the DC power is directly converted to several kilovolts AC without using the sub-transformer. Therefore, the space and cost can be saved with the developed converter.

The system configuration of the developed converter for a PV-PCS is shown in Fig. 2. The voltage range of the DC input from the PV panels is assumed to be up to 600 V. Also, the voltage range of the AC output is assumed to be 6.6 kVrms. Therefore, in the case of the developed converter, the inputs of the SST units are connected in parallel and the outputs are connected in series. Each SST unit consists of a low-voltage side (input side), high-voltage side (output side), and a DC/DC converter. The output voltage is boosted, and the insulation is provided without using a commercial transformer because each SST unit has an HF transformer driven at more than several kilohertz—which is several-hundred-times faster than that of a commercial transformer. The size of a transformer is generally decreased by making the driving frequency high. Therefore, the size of the developed multi-level converter can be much smaller than that of a conventional system with a commercial transformer. Furthermore, thanks to the multi-level voltage output, the output filter can also be smaller.

2.2 Circuit Configuration and Structure of SST Unit

In an SST unit, an LLC converter is used as an isolated DC/DC converter. By applying the LLC converter, the switching losses of the switching devices on the low-voltage side can be reduced because the turn-off current can be made small due to current resonance caused by the magnetizing inductance of the transformer (Lm), the leakage inductance of the transformer (Lr), and the capacitance of the capacitor (Cr). Soft turn-on switching is also made possible with the LLC converter. Therefore, higher switching frequency, along with high conversion efficiency of the LLC converter, can be attained (12)(13). In the case of the circuit configuration shown in Fig. 2, the maximum voltage difference between the low-voltage side (LV side) and the high-voltage side (HV side) is obtained by adding the DC voltage on the LV side to the peak phase voltage on the HV side, which corresponds to a total voltage of about 6.6 kV. Therefore, the performance of the insulation between the LV and HV sides in each SST unit should be enough to withstand 6.6 kV. Furthermore, because of the voltage difference between the LV and HV sides, cooling of the devices is challenging. The devices which need for cooling are on both the LV and HV sides. As mentioned, the insulation between the LV and HV sides are necessary. Therefore, the cooling design which satisfy the performance
of the insulation is needed.

The appearance of a prototype SST unit is shown in Fig. 3, and a schematic view of the sectional structure of the SST unit (as seen from the X-axis direction) is shown in Fig. 4. The prototype has two printed circuit boards (PCBs). The lower one is for the LV side, and the upper one is for the HV side. The cooling fins are equipped in the space between the two PCBs. In this prototype, cooling is provided by forced air. As shown in Fig. 4, air flows from the left side of the SST unit into the space between the two PCBs. By applying this structure, the devices on both the HV and LV sides can be cooled while ensuring good insulation performance because the distance between the cooling fin on the LV side and that on the HV side is designed enough to withstand the voltage stress of 6.6 kV. As a result, the SST unit can be miniaturized, and it can be efficiently cooled. The specifications of the developed system and SST unit are listed in Table 1. The rated power is 300 kW, and 8 SST units are connected per phase (totaling 24 units in the whole system). Therefore, the output of each SST unit is under 1 kV, which means the switching devices whose rated voltage is 1.2 kV can be used. The rated power of the SST unit is 12.5 kW. In the LLC converter in the SST unit, 1.2 kV SiC-MOSFETs are used for the switching devices, and SiC-SBDs are used for the rectifier on the HV side.

3. High-efficiency Control of LLC Converter

A control method for highly efficiently driving the developed converter for PV-PCS—from the viewpoint of operation of the LLC converter—is described below.

3.1 Operation Modes of LLC Converter

Each SST unit has an LLC converter, which controls DC link voltage on the HV side. The circuit of an LLC converter is shown schematically in Fig. 5. Generally, the LLC converter controls the output voltage by means of changing switching frequency \( F_{sw} \) of \( Q_1 \) to \( Q_4 \), and the operation mode of the LLC converter depends on the relationship between \( F_{sw} \) and resonance frequency \( F_r \). It is commonly known that an LLC converter has two resonance frequencies. Hereafter, the higher resonance frequency is focused on and taken as \( F_r \), which is given as

\[
F_r \approx \frac{1}{2\pi \sqrt{L_r C_r}} \tag{1}
\]

where \( L_r \) is the leakage inductance of an HF transformer, and \( C_r \) is the capacitance of a capacitor connected to the windings of the HF transformer in series. The operation mode of an LLC converter varies according to \( F_{sw} \). Waveforms of gate-source voltage \( v_{gs} \) of \( Q_1 \) to \( Q_4 \), current of \( Q_1 \) \( i_{q1} \), and the current of the LV-side windings of the HF transformer \( i_{mh} \) in each operation mode are shown in Fig. 6. In this LLC converter, one pair of switches (\( Q_1 \) and \( Q_4 \)) and the other pair (\( Q_2 \) and \( Q_3 \)) are turned on or off complementarily. When \( F_{sw} < F_r \), the output voltage (i.e., DC link voltage on the HV side) is boosted from the voltage determined by the turn ratio of the HF transformer (i.e., boost mode). In this mode, the switches are turned off after the load current flowing into the HV side becomes zero. Therefore, the turn-off current of the switches (which corresponds to the magnetizing current of the HF transformer) becomes lower than the peak value. As a result, the switching losses can be suppressed. However, in boost mode, the peak current becomes larger than that in other modes; therefore, the conduction losses become larger than that in other modes. When \( F_{sw} \approx F_r \), DC link voltage on the HV side is determined by the turn ratio of the HF transformer (i.e., resonance mode). In other words, the voltage-boost ratio becomes one. In this mode, the switches are turned off after the load current flowing into the HV side becomes zero. Therefore, the turn-off current of the switches (which corresponds to the magnetizing current of the HF transformer) becomes lower than the peak value. As a result, the switching losses can be suppressed. However, in boost mode, the peak current becomes larger than that in other modes; therefore, the conduction losses become larger than that in other modes. When \( F_{sw} > F_r \), DC link voltage on the HV side is determined by the turn ratio of the HF transformer (i.e., resonance mode). In other words, the voltage-boost ratio becomes one. In this mode, the switches are turned off when the load current becomes zero. Therefore, switching losses of the switches can be suppressed in the same manner as in boost mode. Furthermore, the peak current becomes lower than that in boost mode. Therefore, the conduction losses can also be suppressed, thereby increasing efficiency. When \( F_{sw} > F_r \), DC link voltage is stepped down from that determined by the turn ratio of the HF transformer.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated system power</td>
<td>300 kW</td>
</tr>
<tr>
<td>Number of units per phase</td>
<td>8</td>
</tr>
<tr>
<td>Number of SST units (whole system)</td>
<td>24</td>
</tr>
<tr>
<td>Rated power of each SST unit</td>
<td>12.5 kW</td>
</tr>
<tr>
<td>DC-input-voltage range</td>
<td>320 ~ 600 V</td>
</tr>
<tr>
<td>MPPT-voltage range</td>
<td>400 ~ 540 V</td>
</tr>
<tr>
<td>Insulation voltage (between LV and HV sides)</td>
<td>AC 6.6 kVrms</td>
</tr>
</tbody>
</table>
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3.2 Cooperative Control of DC Link Voltage for LLC Converter

As a solution to the problem described in Section 3.1, a method to cooperatively control DC link voltage (and thus enhance efficiency compared to the conventional control method) is proposed. For example, in the case of the conventional method, if the input voltage is high, the LLC converter operates in buck mode, resulting in low efficiency because of large switching losses. On the other hand, in the case of the proposed method, the voltage-boost ratio between the input and output voltages (DC link voltage) is kept to 1 in a certain input-voltage range. As a result, DC link voltage changes according to the input voltage. By adopting the proposed method, the LLC converter can operate in resonance mode in a wider input-voltage range than that possible with the conventional method. As a result, it is possible to enhance the efficiency of the LLC converter. The relationships between input voltage and DC link voltage in the case of applying the conventional and proposed methods are shown in Figs. 7 and 8, respectively. In the case of the conventional method shown in Fig. 7, DC link voltage is kept constant in any input voltage. Therefore, the high-efficiency operation of the LLC converter can only be achieved near the resonance point, which is a small part of the MPPT range. On the other hand, in the case of the proposed method shown in Fig. 8, DC link voltage is changed according to the input voltage. In detail, DC link voltage is controlled so that DC link voltage is proportional to the input voltage when the input voltage becomes over a certain value. The value means the voltage that the voltage boosting ratio becomes 1 with considering the turn ratio of an HF transformer. Therefore, by applying the proposed method, the LLC converter can keep operating with the voltage-boost ratio of 1. In other words, the LLC converter can operate in the resonance mode over the wide voltage range, resulting in high-efficiency operation of the LLC converter. In Fig. 8, DC link voltage is proportional to the input voltage from 640 V to 720 V. The minimum value of 640 V is determined by the limitation of the modulation rate of the inverter in each SST unit. Furthermore, the maximum voltage of 720 V is determined by the rated voltage of DC

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(i.e., buck mode). In this mode, the switches are turned off before the load current reaches zero. Therefore, the turn-off current becomes larger than that in other modes, resulting in larger switching losses than those in other modes. As explained above, the efficiency of the LLC converter becomes high when the LLC converter operates in resonance mode; on the other hand, if it operates in boost and buck modes, the efficiency decreases. Therefore, to apply the LLC converter to a PV-PCS, the high-efficiency operation of the LLC converter becomes a problem because the input voltage may fluctuate with time or weather, meaning the voltage-boost ratio always changes.

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Fig. 6. Operation modes of the LLC converter

Fig. 7. Relationship between input voltage and DC link voltage when the conventional control method is applied

Fig. 8. Relationship between input voltage and DC link voltage when the proposed control method is applied
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Table 2. Parameters of LLC converter in prototype SST unit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching frequency (F_{sw})</td>
<td>30 – 60 kHz</td>
</tr>
<tr>
<td>Resonant frequency (F_r)</td>
<td>48 kHz</td>
</tr>
<tr>
<td>Magnetizing inductance (L_m)</td>
<td>140 (\mu)H</td>
</tr>
<tr>
<td>Leakage inductance (L_r)</td>
<td>24.5 (\mu)H</td>
</tr>
<tr>
<td>Resonant capacitance (C_r)</td>
<td>450 nF</td>
</tr>
</tbody>
</table>

Table 3. Loss analysis conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Input voltage (V)</th>
<th>DC-link voltage (V)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>500</td>
<td>640</td>
<td>12.5</td>
</tr>
<tr>
<td>Proposed</td>
<td>500</td>
<td>720</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Table 4. Experimental conditions (half voltage conditions)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Input voltage (V)</th>
<th>DC-link voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250</td>
<td>360</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>320</td>
</tr>
</tbody>
</table>

link capacitors (800 V). Incidentally, the effect to the inverter loss is quite small by using the proposed method because of changing DC link voltage. The inverter output of each SST unit is connected in series (in this case, 8 units), which means that switching frequency of each inverter doesn’t have to set high (for example, several hundreds Hz). Therefore, the increase of the switching loss is few.

4. Evaluation of Prototype SST Unit

To evaluate the proposed method, a prototype SST unit shown in Fig. 3 was designed and implemented. The circuit parameter is shown in Table 2. Firstly, the LLC converter losses in the case of the conventional and the proposed method are compared analytically. Secondary, the experimental evaluations are implemented. The measured efficiency according to the load characteristics under two input voltages are presented.

4.1 LLC Converter Loss Analysis

Firstly, in order to evaluate the proposed method, the LLC converter losses are analyzed under the rated load condition. The analysis conditions are shown in Table 3. Under the conventional condition, DC link voltage is controlled of 640 V at the input voltage of 500 V. On the other hand, under the proposed condition, DC link voltage is controlled of 720 V at the same input voltage as the conventional condition. Furthermore, the output power is 12.5 kW (rated load) in both conditions. The circuit parameters are assumed as the prototype SST unit shown in Table 2. In this analysis, the current values such as the turn-off current which is needed for the loss calculation are estimated by the circuit simulation.

Figure 9 shows the loss calculation results. In the case of the conventional condition, the switching loss is dominant in the total loss. In this case, the LLC converter operates in the buck mode, which results in large turn-off current. This is the reason why the switching loss becomes dominant. On the other hand, in the case proposed condition, the switching loss becomes smaller than that of the conventional. This is because the LLC converter can operate in the resonant mode, which results in the lower turn-off current. As a result, the total loss decreases by 13.3% by the proposed method. Therefore, the validity of the proposed method is confirmed analytically.

4.2 Experimental Conditions

Figure 10 shows the experimental configuration. A DC electronic load is used as the resistance load, and a power analyzer which has multiple channels is used for measuring the input and output power to calculate the efficiency. In the experiments, two voltage conditions are considered. The experimental conditions are listed in Table 4. As for condition 1, input voltage was 250 V, and DC link voltage was 360 V. As for condition 2, input voltage was 200 V, which was 50 V (20%) lower than that in condition 1, and DC link voltage was 320 V. Thus, DC link voltage was changed according to input voltage. In these conditions, input voltage and DC link voltage were set to about half of the rated voltage because of the limitation of the experimental equipment. Under these conditions, the efficiency of the prototype SST unit was measured by varying the load factor from 5% to 100%. Moreover, to confirm the validity of the experiments under the half-voltage condition, the experiment was also performed under the rated-voltage condition. In that experiment, input voltage was 475 V, and DC link voltage was 640 V. Also, in the experiments, the efficiency was measured by varying the load factor from 5% (625 W) to 100% (12.5 kW).

4.3 Experimental Results

The waveforms of each voltage and current when the load factor is 100% under conditions 1 and 2 are shown in Fig. 11. \(v_{gs}\), \(v_{tr}\), and \(v_{ds}\) are the voltages between the gate and source of an SiC-MOSFET, between the terminals of the HF transformer on the LV side, and between the drain and source of the SiC-MOSFET, respectively, and \(i_t\) is the current of the HF transformer on the LV side. It is clear from Fig. 11(a) that \(i_t\) becomes almost
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Fig. 11. Measured waveforms of voltage and current in each operation mode

Fig. 12. Measured waveforms of the voltage and current under the rated voltage condition

Fig. 13. Measured efficiency of the developed LLC converter with the proposed control

Fig. 14. Measured efficiency of the LLC converter under the rated-voltage condition

5. Conclusion

The concept of a multilevel power-conversion system consisting of multiple SST units for photovoltaic generation was sinusoidal, indicating that the LLC converter operates in resonance mode. Therefore, the turn-off current is lower than the peak, resulting in high-efficiency operation. It is clear from Fig. 11(b) that \( i_tr \) also becomes sinusoidal; however, the period in which the magnetizing current flows is slightly longer than that under condition 1. This result means that the LLC converter operates in so-called “light” boost mode. Therefore, as under condition 1, turn-off current is lower than the peak. Furthermore, the experimental waveforms under the rated voltage condition are shown in Fig. 12. The current of \( Q_1 \) \( i_{Q1} \) is shown instead of \( v_tr \). From the waveforms, \( i_tr \) becomes also sinusoidal in the same manner as under condition 1. The measured efficiencies under conditions 1 and 2 are shown in Fig. 13. It is clear that the measured efficiencies at a load factor of 100% under conditions 1 and 2 are over 98%. Moreover, even at load factor of 10%, the efficiencies are over 94%. Under condition 1, maximum efficiency is 98.3% at load factor of 70%. As mentioned above, the efficiency under condition 1 is almost the same as that under condition 2. This means that the high efficiency operation can be kept even if the input voltage changes by the proposed method. Therefore, the validity of the proposed method was experimentally confirmed. Additionally, the measured efficiency under the rated-voltage condition is shown in Fig. 14. The maximum efficiency is 98.4% at load factor of 70%, and that at load factor of 100% (12.5 kW) is 98.3%. Moreover, efficiency at load factor of 10% is over 94%. It is concluded from these results that the experimental results under the half-voltage condition can be used instead of those obtained under the rated voltage condition. Furthermore, the loss calculation results shown in Fig. 9 and the measured loss are compared in Fig. 15. The both results correspond well, and the error is only 3.7%. Therefore, the validity of the loss calculation results is also confirmed.
introduced. Furthermore, to realize high-efficiency operation of the LLC converter, which is key component of the SST unit, over a wide input-voltage range, a method for cooperatively controlling DC link voltage was proposed. To evaluate the validity of the proposed method, a prototype SST unit was experimentally evaluated under the two input-voltage conditions. According to the experimental results, the efficiencies of the prototype under both conditions were almost the same. This result means that when the proposed method is applied, the LLC converter achieves high-efficiency operation over a wide input-voltage range. In particular, it achieves maximum efficiency of 98.4% and efficiency under a light-load condition (such as load factor of 10%) of over 94%.

References


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